ECE-4603

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Supplement to Chapters 3 and 5

- Analog to Digital Conversion
- Bandwidth versus Capacity
- Nyquist and Shannon equations.
- SignalDegradation
- Basebase and Broadband Encoding

Data & Computer Comm., p 95-98, 148-155

Analog and Digital Signals

Analog Signal - value varies continuously

- **Sound - air pressure wave, can be converted to analog voltage or current wave by microphone.**
- **Electrical (analog) voice frequency signals - can be converted to sound by loudspeaker.**
- **Picture - light (color, brightness) varies continuously with position.**

Digital Signals - strings of discrete values which can be represented by binary numbers, strings of one's and zeros.

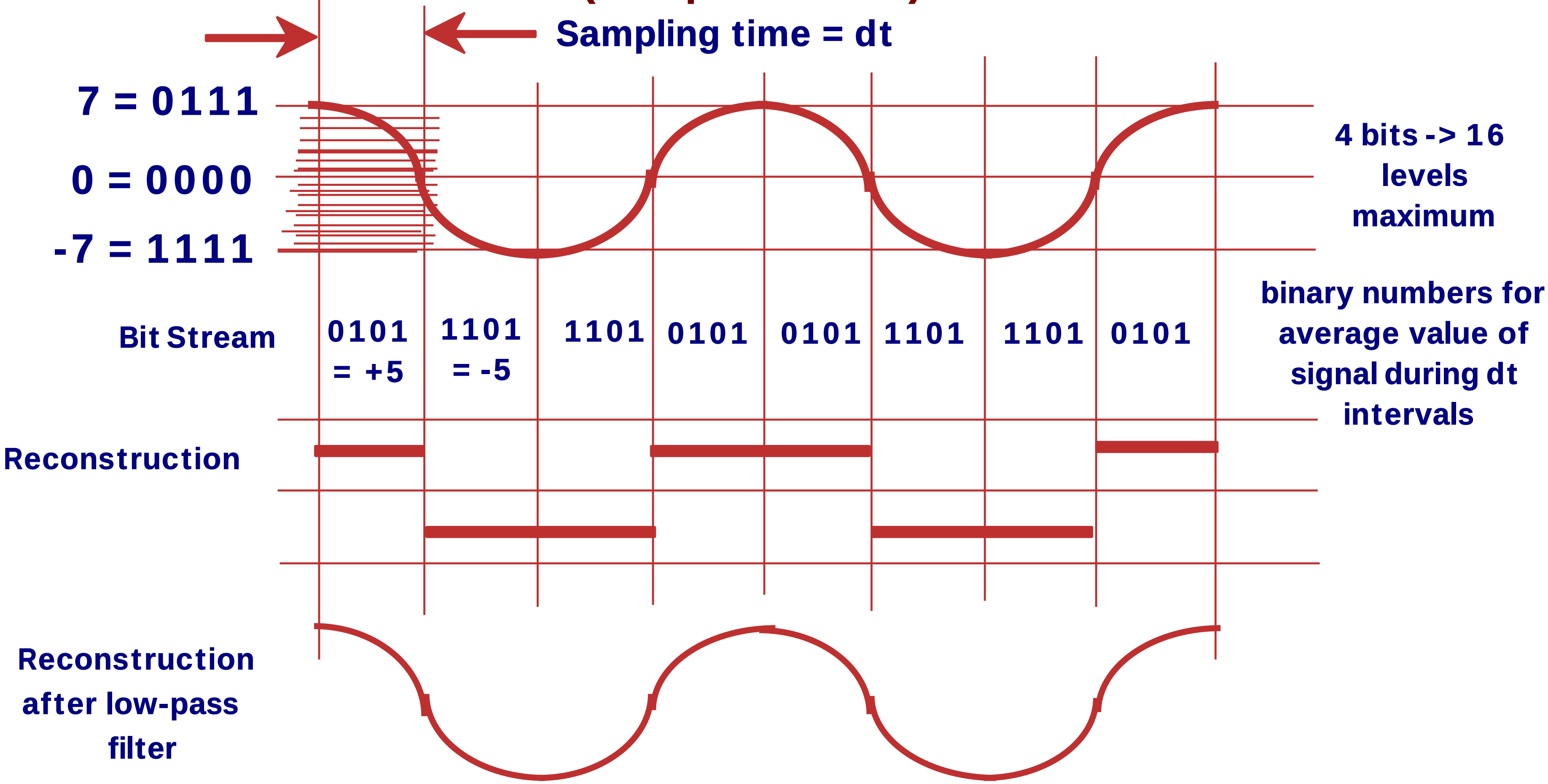
- **Time-varying analog signals are converted by averaging the value over a time increment and assigning a binary value.**
- **Images are divided into small areas (pixels), then color and brightness are averaged over each pixel and transmitted are stored in digital memory sequentially.**

Conversion of Analog to Digital

Time increments, dt, must be small enough to capture highest-frequency components of interest.

The number of Amplitude Increments, n, must enough to give an adequately-accurate estimation of the analog signal.

The bit rate is n/dt (bits per second).



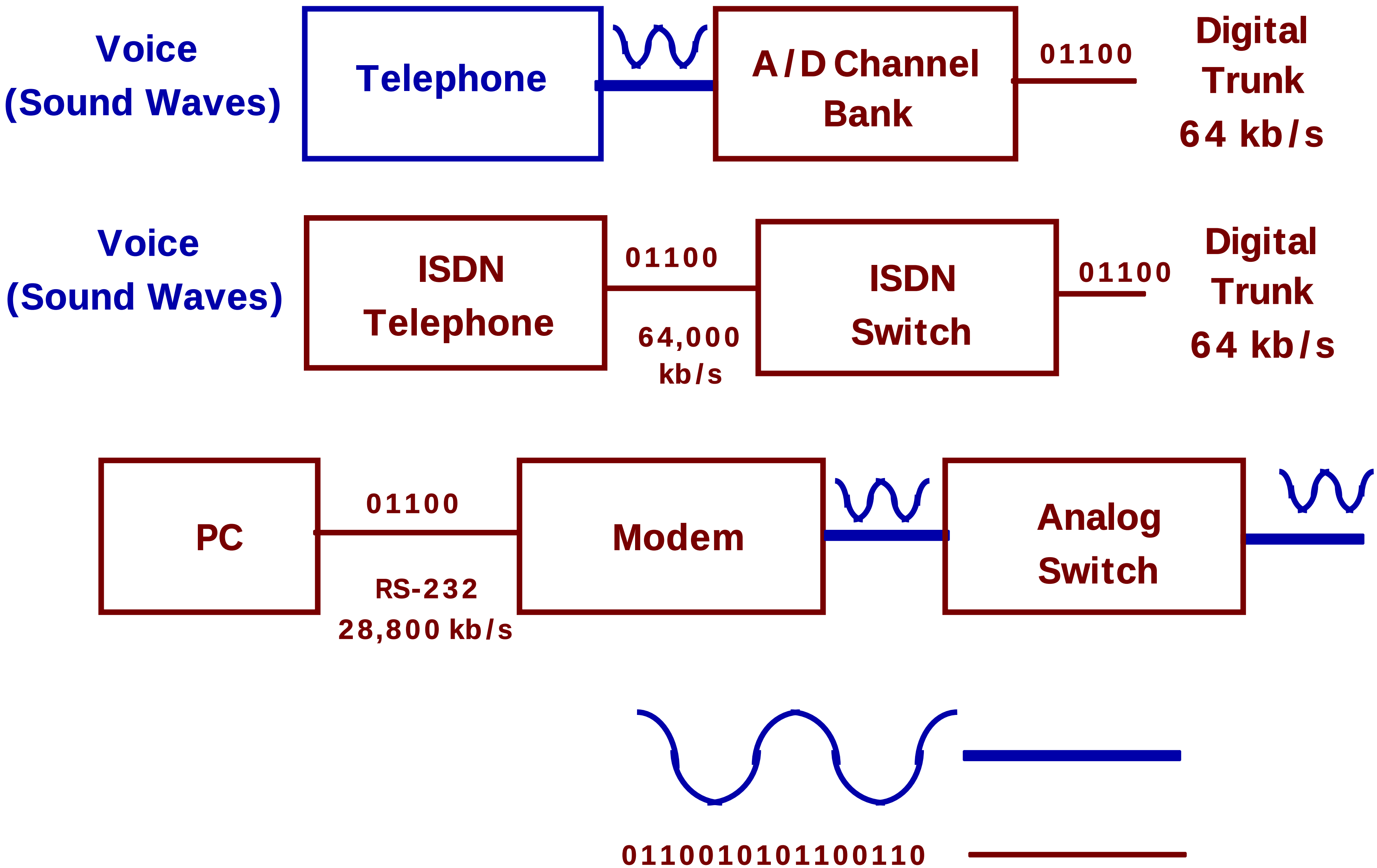
Digital Voice

- Voice is recognizable and intelligible when frequency range is limited to 300 to 3400 Hz (Hertz = cycles/second) and quantization noise < -20 dB.
- Telephone standard is to digitize 8000 times per second (dt=125 ms) and to use 128 levels (8 bits including sign).
- This results in a bit rate for a voice channel of 64,000 b/s.

Digital Music

- Music requires a frequency range up to 18,000 Hz and quantization noise < -65 dB.
- CD music is digitized 44,100 times per second (dt=23 µs) into 32,000 levels (16 bits including sign).
- This results in a bit rate for a CD music channel of 710,000 b/s (times 2 for stereo).

Analog and Digital Signals



Channel Bandwidth versus Capacity

- <u>Capacity</u> = Rate in bits/second (b/s) that bits can be transmitted.
- <u>Bandwidth</u> = Frequency range (width)of the channel (Hertz).
-

Maximum Baud Rate (symbols/sec), B = 2 H

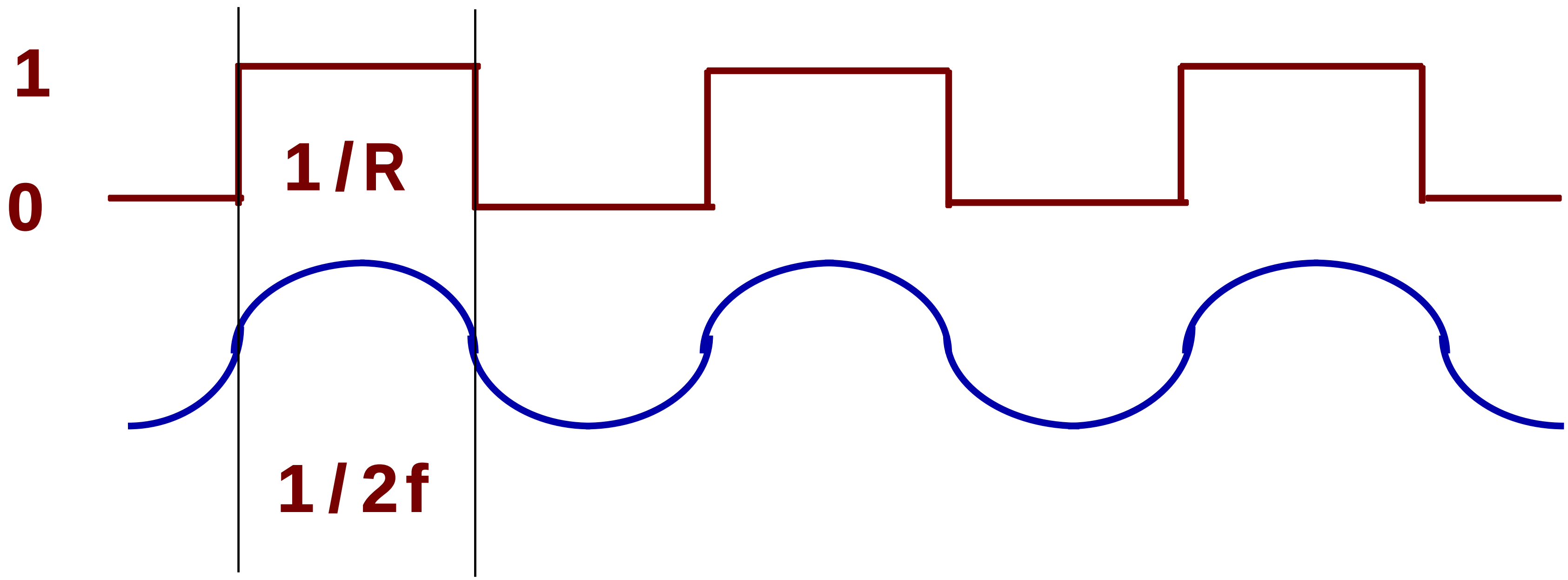
- <u>Noise</u> = Unpredictable deviation of received value due to all causes (probability bounded by acceptable error rate).
  - Thermalnoise, Crosstalk, Impulse, Intermodulation, ...
- <u>Nyquist Theorem</u> for a noiseless channel: given a bandwidth H and a signal with L different levels, the capacity C is given by:

Maximum Data Rate (bits/sec), $C = 2 H \log_2 (L)$

- <u>Shannon's Theorem</u> for a noisy channel with signal to noise ratio S/N is given by:

$$C = H \log_2 (1+S/N)$$

Maximum Symbols (Baud) per Second

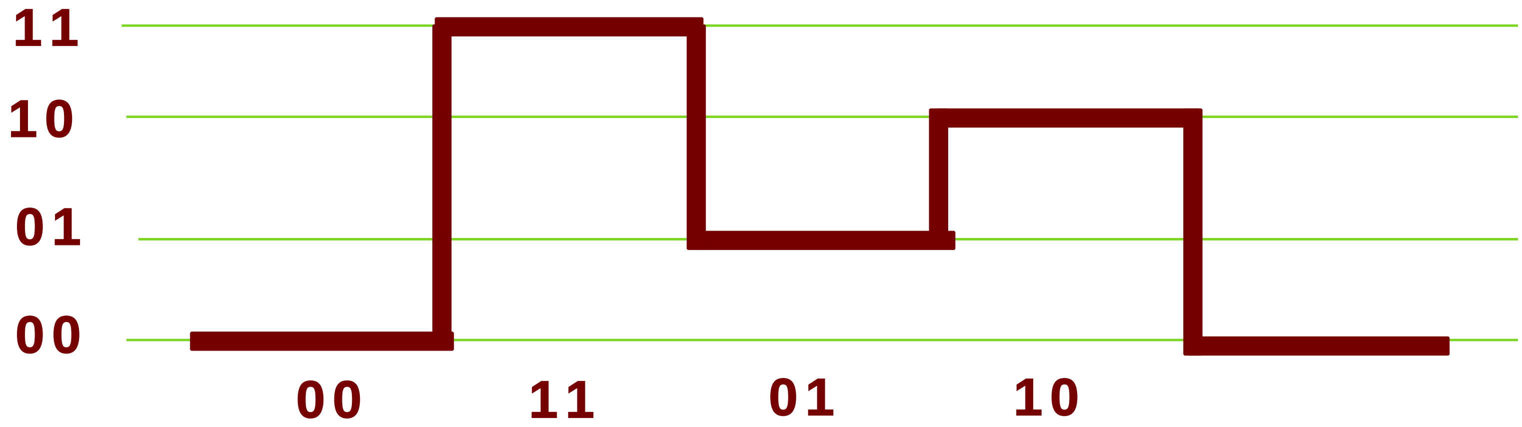


Since Bandwidth (H) = fmax:

Rmax = 2 fmax =2 H

The maximum number of independent time intervals (symbols) is equal to twice the bandwidth.

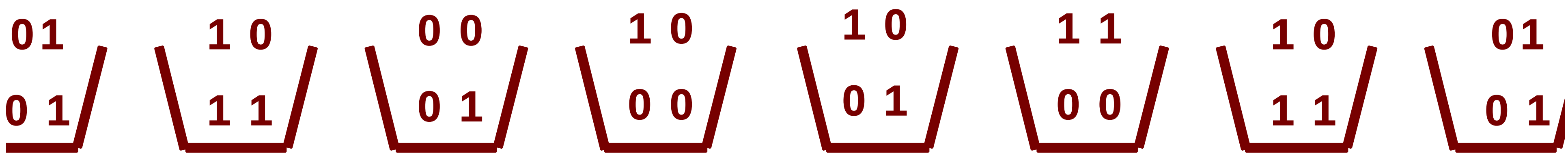
Number of Bits per Symbol



Two bits per symbol requires 4 levels.

The number of bits per level, N_{bL}, is $\log_2(L)$.

Levels	Bits
2	1
4	2
8	3
16	4
32	5
64	6



Think of a "Baud" as a "Bucket" that holds a certain number of bits.

The number of bits per second that pass a certain point (or arrive at a node) =

the number of Baud (Buckets) per second multiplied by

the number of bits carried by each Baud (in each Bucket).

Simplified Concept of Shannon's Law

The Capacity (maximum bit rate) is equal to the maximum number of symbols per second (2 x Bandwidth) multiplied by the number of bits per symbol { log2 (L) }. -

Nyquist : $C = 2 H \log_2(L)$

Intuitively, the maximum number of levels with an maximum signal voltage Vs is approximately Vs / Vn, where Vn is the noise voltage (separation voltage between levels needed to reduce errors due to noise to acceptable value). Claude Shannon (father of Information theory) found a more exact value as a function of the ratio of signal power S to noise power N.

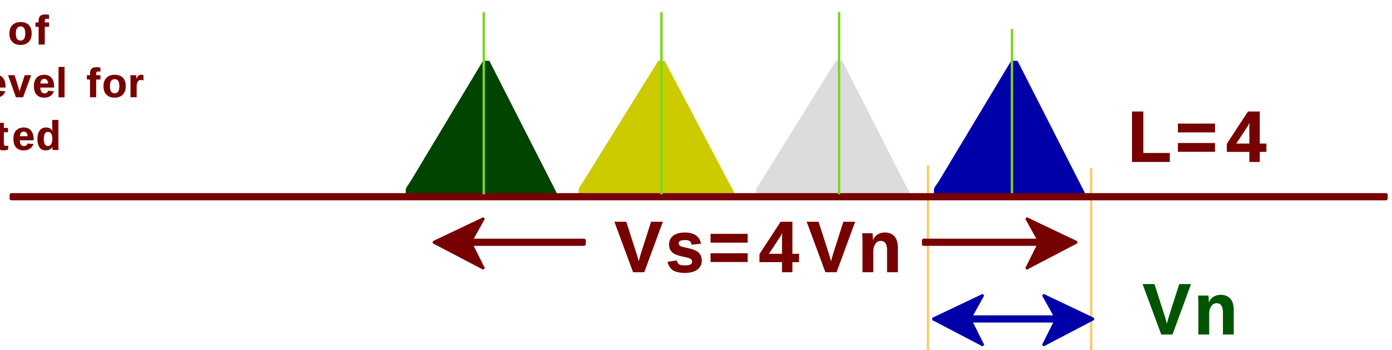
Shannon : $C \le 2H \log_2(\sqrt{(S+N)} / \sqrt{N})$

$\le H \log_2(S/N + 1)$

to match Nyquist : $L \le \sqrt{(S/N + 1)} = \sqrt{(S+N)} / \sqrt{N}$

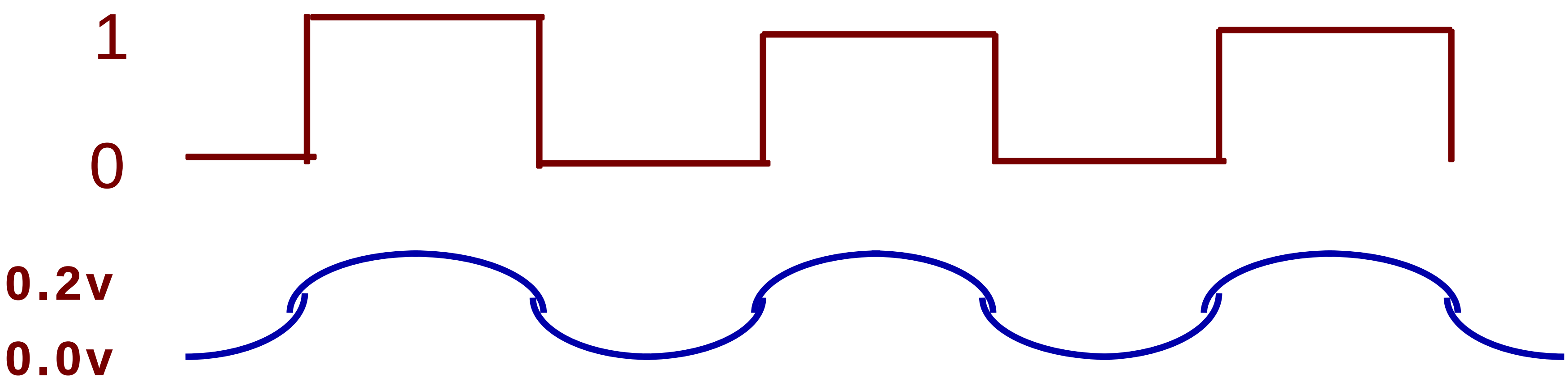
L <= (signal + noise voltage) / (noise voltage)

Probability of received level for 4 transmitted levels.



Signal Degradation

All real signals are analog by nature. While the transmitter may send exact discrete levels into a physical transmission line, the receiver sees a degraded signal and must decide which discrete level expected is closest.



Attenuation - lost of strength (amplitude)

Bandwidth cutoff - lost of high-frequency components.

Data Transmission Types

Analog Baseband

- Voice Telephone

Digital Baseband

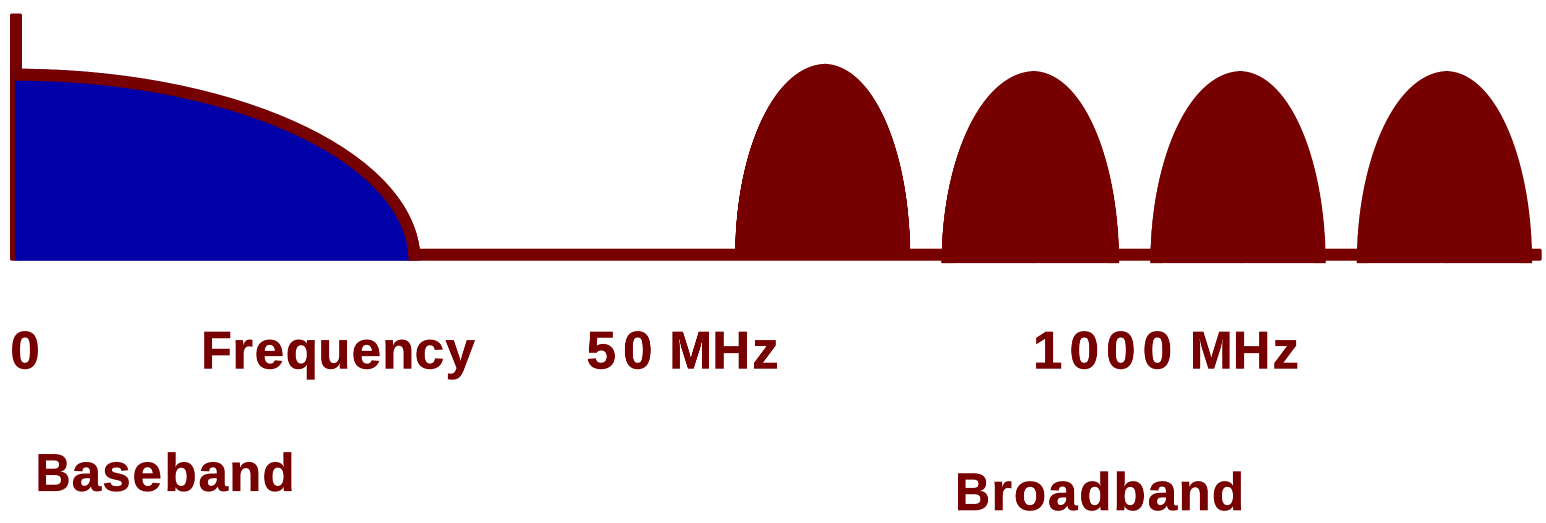
- ISDN Voice
- Ethernet
- PC Comm Port

Analog Broadband

- AM, FM, TV, Cellular (AMPS)

Digital Broadband

- Direct-TV (satellite)
- PCS, Digital Cellular
- Digital CATV



Data Encoding Schemes

Baseband - frequency range is from 0 Hz to f_{max}

$(B = f_{max})$

Broadband - frequency range is from f_{min} to f_{max}

$(B = f_{max} - f_{min})$

With broadband signals, data is modulated onto a carrier wave whose frequency is at the center of the band. Common types of modulation are:

- Amplitude Shift Keying (ASK)
- Frequency Shift Keying (FSK)
- Phase Shift Keying (PSK)
- Quadrature Phase Shift Keying (QPSK)
- Quadrature Amplitude Modulation (QAM)

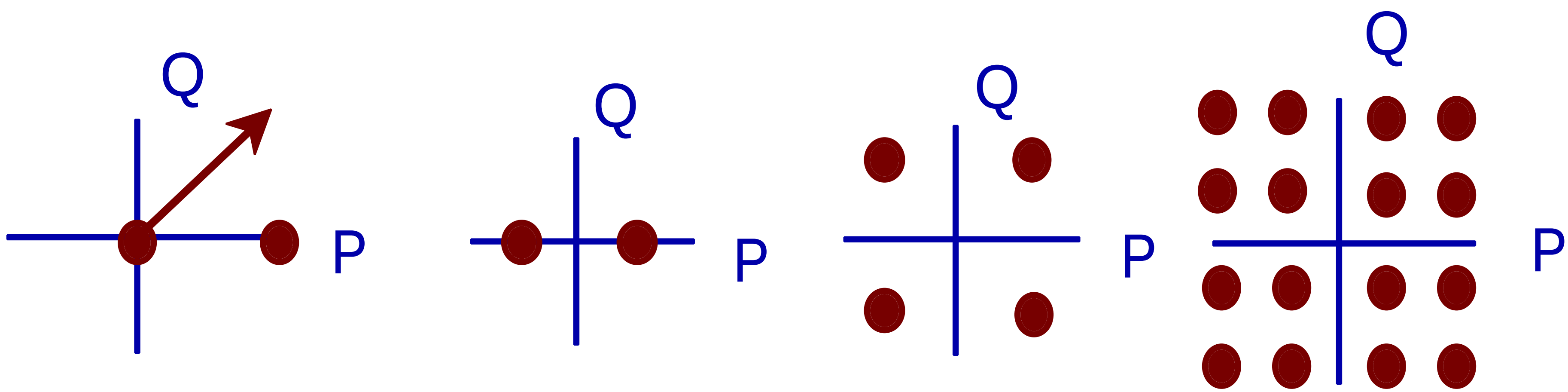
With all commonly-used Broadband modulation schemes:

Bandwidth (Hz) = Baud Rate (Baud/second)

Broadband Modulation Encoding

A sine wave with arbitrary amplitude A and phase ø can be represented by the amplitude of the in-phase and quadrature components, P & Q:

$$V(t) = A\ \mathrm{sine}(wt+ø) = P\ \mathrm{sine}(wt) + Q\ \mathrm{sine}(wt+90)$$



ASK	PSK	QPSK	QAM
1 bit	1 bit	2 bits	4 bits

Each state is represented by a dot in the "constellation"diagram.

Baseband Encoding Schemes

Problems to overcome

- **Transitions needed to synchronize receiver bit clock**
- **DC reference level needs to be maintained**